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A rapid graphical method of evaluating the chromatic properties of a television display

No. 1972/30

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

A RAPID GRAPHICAL METHOD OF EVALUATING THE CHROMATIC PROPERTIES OF A TELEVISION DISPLAY

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(PH-95)

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Summary

The use of a set of six charts or 'error diagrams' is described, in which the chromaticity and relative luminance of a particular test colour, when reproduced by a colour television display, may be immediately obtained knowing the effective chromaticities of the three display primaries. An assessment of the accuracy of the method is also given.

1. Introduction

The colour-analysis characteristics of colour cameras are based on the assumption that the colour display will contain the set of phosphors whose displayed chromaticities are as specified for the 625-line System I transmissions.[1] These 'primary chromaticities' are shown in Table 1 in terms of the 1960 C.I.E. uniform chromaticity scale (UCS) co-ordinates (u, v). In practical display tubes,* however, the primary chromaticities rarely correspond precisely to these specified values. Given the linear** colour-separation signal values (R_c, G_c, B_c) corresponding to a particular scene colour, the primary chromaticities, and the display white-point chromaticity, the tristimulus values (U_c, V_c, W_c) of the displayed colour may be calculated using the relationship

$$\begin{bmatrix} U_c \\ V_c \\ W_c \end{bmatrix} = \begin{bmatrix} M \end{bmatrix} \begin{bmatrix} R_c \\ G_c \\ B_c \end{bmatrix} \qquad (1)$$

where $[M]$ is a 3 x 3 matrix whose coefficients are related to the primary and white-point chromaticities and to the required luminance normalisation.[2,3] The chromaticity co-ordinates (u_c, v_c) of the displayed colour may then be calculated since,

$$u_c = \frac{U_c}{U_c + V_c + W_c}$$

and

$$v_c = \frac{V_c}{U_c + V_c + W_c} \qquad (2)$$

* In this report only the 'effective' primary chromaticities (i.e. the chromaticities as measured in the display tube under consideration) are of interest.

** A linear overall transfer characteristic of the signal chain is assumed.

Furthermore, the relative luminance is given directly by the magnitude of V_c. It can be seen from Equations (1) and (2) that it is a relatively simple matter, once the matrix $[M]$ has been derived, to determine the chromaticities and luminance values of displayed colours corresponding to different sets of colour-separation signal values. The rapid determination of the effect of changes of primary chromaticity using a given set of colour-separation signal values, however, is not such a simple operation, particularly as a matrix inversion is involved in the derivation of the matrix $[M]$. The method to be outlined in this report enables the effect of such changes in primary chromaticity to be rapidly determined with reasonable accuracy for a particular scene colour.

TABLE 1

Primary Chromaticities for System I Phosphors

Phosphor	Chromaticity Co-ordinates	
	u	v
Red	0·451	0·349
Green	0·121	0·374
Blue	0·175	0·105

2. Outline of the method of determining the effect of changes of primary chromaticity

2.1. The effect on the reproduced chromaticity

The method of determining the effect of changes of primary chromaticity on the reproduced chromaticity of a particular scene colour will be described assuming, to begin with, that only the red phosphor is subject to changes in the red primary chromaticity, the green and blue phosphors giving primary chromaticities corresponding to the specified

System I values. The 'correct' value of reproduced chromaticity (u_{co}, v_{co}) is obtained when the red primary chromaticity also has the specified System I value (u_{ro}, v_{ro}). This chromaticity co-ordinate is shown as a '+' sign in Fig. 1, which is a chromaticity diagram showing reproduced scene-colour chromaticities in the immediate neighbourhood of this correct value. No other red primary chromaticity will give rise to this reproduced chromaticity and the point may therefore be labelled with the red primary chromaticity. This labelling is shown in square brackets to distinguish it from the cartesian co-ordinates (u_{co}, v_{co}) of the point.

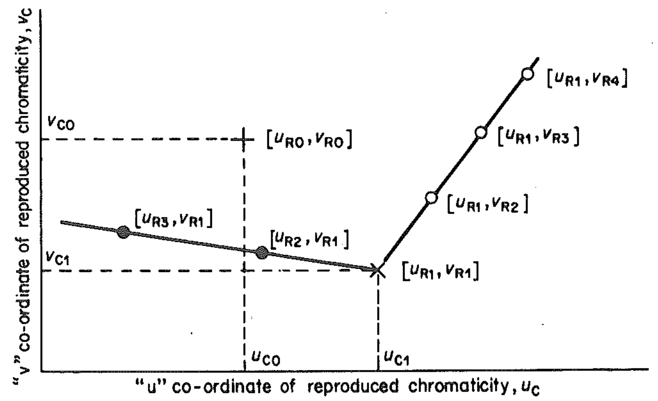

Fig. 1 - Chromaticity diagram illustrating effect of perturbations of red phosphor chromaticity

Another value of reproduced chromaticity (u_{c1}, v_{c1}), corresponding to a perturbed red primary chromaticity (u_{r1}, v_{r1}), is shown in Fig. 1 as a 'x' sign and is again appropriately labelled. If the v co-ordinate value of the red primary chromaticity is now varied while holding the u co-ordinate value constant, it is found that the resulting locus of the point in Fig. 1 is a straight line (as shown by the open circles): similarly, if the u co-ordinate of the red primary chromaticity is varied while holding the v co-ordinate constant, the point moves along another straight line (full circles in Fig. 1).* It can thus be seen that a co-ordinate grid in u_r and v_r may be superimposed on the chromaticity diagram describing the reproduced scene chromaticity (u_c, v_c), as shown in Fig. 2. Using this grid, the reproduced scene chromaticity for the specified scene colour corresponding to any red primary chromaticity may be immediately determined.

The quantity of interest is usually not so much the absolute value of reproduced chromaticity as the error in reproduction relative to a certain standard value. The axes of the chromaticity diagram can therefore be conveniently re-scaled (Fig. 3) so that the origin lies at the point of zero chromatic error (i.e. when the red primary chromaticity has the specified System I value (u_{ro}, v_{ro})), distances along the axes now being expressed in terms of 'chromaticity error units' (E_{uR}, E_{vR}). This re-scaled chromaticity diagram may be described as the 'red chromaticity error diagram' for the particular test colour concerned.

* These two straight lines are not necessarily orthogonal, neither are the successive points corresponding to equal increments of u_r or v_r equi-spaced along them.

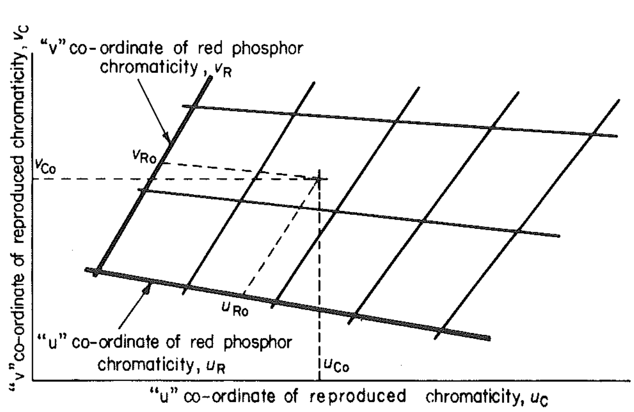

Fig. 2 - Chromaticity diagram illustrating co-ordinate grid of phosphor chromaticity

In an exactly analogous manner, green and blue chromaticity error diagrams may be derived. In each diagram the error-unit axes are identical: however, the primary chromaticity co-ordinate grids are likely to be very dissimilar in appearance. It may now be postulated that the overall error in reproduced chromaticity, in a situation where none of the display primaries corresponds to its specified System I value, is equal to the vector sum of the individual errors exhibited in each of the three chromaticity error diagrams. Strictly speaking this is only an approximation, since the primary chromaticity grids in each diagram have been constructed assuming that the primary chromaticities not under consideration have precisely their System I values: nevertheless, for the errors in primary chromaticity usually encountered in practice, the approximation is good and a reasonably accurate estimate of the overall chromaticity error in reproduction is obtained. Examples are given in Section 3.2 showing the degree of accuracy which may be expected.

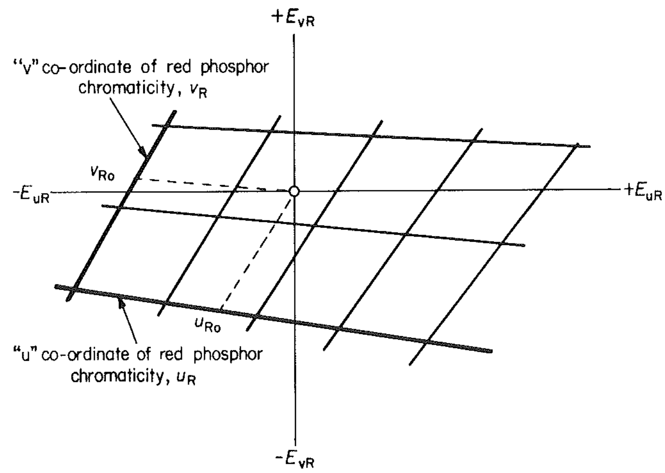

Fig. 3 - Illustration of red chromaticity error diagram

2.2. The effect on the reproduced luminance

Accuracy in reproduced scene chromaticity is usually the predominant factor which determines the acceptability or otherwise of a particular combination of primary chromaticities. Nevertheless, it is useful to know the magnitude of the associated accuracy with which the relative luminance of the colour is reproduced. The effect of changes in

primary chromaticity on the reproduced relative luminance of a particular scene colour will again be described in terms of perturbations of the red primary chromaticity, the other two primary chromaticities retaining their specified System I values. A set of red primary chromaticities (u_r, v_r) may be determined having the property that each member of the set gives the same error of relative luminance. It is found that the locus of such a set of points, when plotted on a chromaticity diagram, is a straight line: such a straight line therefore represents a 'contour' of a certain luminance error. Fig. 4, for example, shows a portion of the chromaticity diagram in the neighbourhood of the red primary chromaticity. The point corresponding to the System I value (u_{ro}, v_{ro}) is shown at a '+' sign. The contour of zero luminance error must clearly pass through this point: other red primary chromaticities (u_{r1}, v_{r1}) and (u_{r2}, v_{r2}) lying on this contour (open circles in Fig. 4) also give zero luminance error. Similarly, the red primary chromaticities (u_{r3}, v_{r3}), (u_{r4}, v_{r4}) and (u_{r5}, v_{r5}) all give rise to "x%" luminance error.

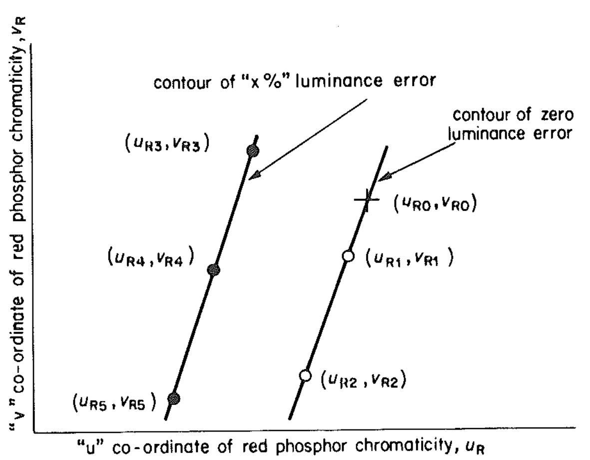

Fig. 4 - Derivation of red luminance error diagram

The contour diagram shown in Fig. 4 may be described as the 'red luminance error diagram' for the particular test colour concerned. In an exactly analogous manner, green and blue luminance error diagrams may be derived. These diagrams may be used to estimate the overall luminance error in the case where none of the primary chromaticities correspond to the specified System I value, within the same limitations of accuracy as discussed in Section 2.1; examples of the degree of accuracy attainable are shown in Section 3.3. In fact, if the luminance-error contours shown on (say) the red luminance error diagram (see Fig. 4) were to be replotted on the red chromaticity error diagram (see Fig. 3), using the co-ordinate grid in u_r and v_r on this latter diagram for the purpose, both the chromaticity and luminance error information would be contained in one diagram. In the present report, however, the two diagrams will be kept separate in the interests of greater clarity.

3. Application of the method for a particular test colour

3.1. The choice of test colour

It is generally agreed that the acceptable reproduction of human facial skin colours presents one of the most severe tests of a colour television display. Such a colour therefore represents a suitable 'first choice' for use in the rapid method of determining the effects of display primary chromaticity perturbations. Figs. A1 – A6 have been derived using Test Colour No. 17 of the BBC standard set of test colours:[4] this is a skin tone having the parameters shown in Table 2.

TABLE 2

Parameters of Test Colour No. 17

Linear colour separation signals			Chromaticity co-ordinates		
R	G	B	u	v	Luminance (white = 1·0)
59·90	40·42	30·67	0·2221	0·3256	0·4404

The colour-separation signal values shown in this table assume 'ideal' analysis for the System I primary chromaticities and further assume scene illumination and display white point corresponding to Illuminant D_{65} (u = 0·1978, v = 0·3122). The values in the table are thus mutually consistent (i.e. with a linear overall transfer characteristic, the specified colour-separation signals will give rise to a displayed colour of the indicated chromaticity and luminance, if the displayed primary chromaticities correspond to the specified System I values).

3.2. Chromaticity error diagrams

Figs. A1, A2 and A3 (see Appendix) show respectively the red, green and blue chromaticity error diagrams for Test Colour No. 17. The error units conform to the relationships

$$E_u = u_{cp} - 0{\cdot}2221$$

$$\text{and} \qquad E_v = v_{cp} - 0{\cdot}3256$$

where (u_{cp}, v_{cp}) are the chromaticity co-ordinates of the displayed colour for the 'practical' primary chromaticities under consideration.

In each diagram the primary chromaticity co-ordinate grids are bounded by a 'spectrum locus' line: this corresponds to the portion of the spectrum locus adjacent to the primary chromaticity under consideration and indicates the limit of practical primary chromaticities. In Fig. A1 the relatively close spacing of the lines of constant u_r in the primary chromaticity co-ordinate grid indicates that reproduced chromaticity changes in Test Colour 17 are relatively insensitive to changes in the u co-ordinate of the red primary chromaticity. Fig. A3 similarly indicates insensitivity to the v co-ordinate of the blue primary chromaticity (especially in the region of the specified System I chromaticity) but also indicates considerable sensitivity to the u co-ordinate of this primary.

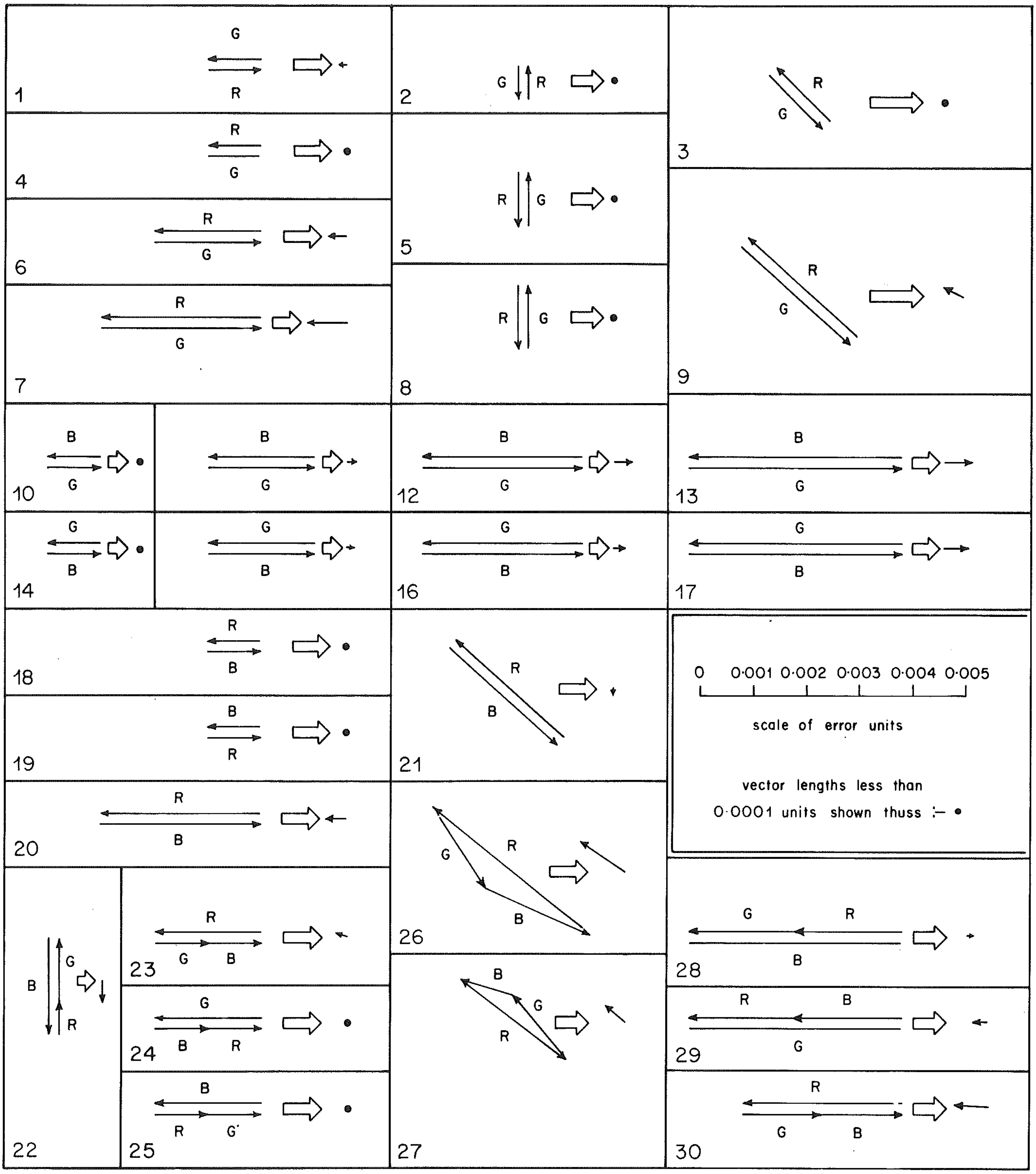

Fig. 5 - Sets of 'compensating' error vectors

Fig. 5 shows comparisons between reproduced test-colour chromaticities, predicted on the one hand from the chromaticity error diagrams and obtained on the other hand by direct calculation using Equations (1) and (2). 'Compensating' pairs or trios of primary chromaticities are considered, so that in each case the sum of the corresponding error vectors is zero. (It is interesting to note the directions of movement of the primary chromaticity co-ordinates involved in these cases of compensating error: for example, it is at first sight rather surprising that changes of the u co-ordinate values of the red and green primary chromaticities in the same direction give rise to such compensation

as far as Test Colour 17 is concerned.) The error vectors are shown by line arrows labelled 'R', 'G' or 'B' to indicate the respective correspondence to the red, green or blue primary chromaticity. The block arrow on the right-hand side of each vector combination points to a 'reliability vector' representing (on the same scale) the departure of the directly-calculated reproduced chromaticity from the value predicted from the error diagrams. It can be seen that, as might be expected, the reliability-vector magnitude is, in very general terms, related to the magnitudes of the individual error vectors. This is shown more clearly in Fig. 6, in which the reliability-vector magnitude is plotted as a function of the sum of the corresponding error-vector magnitudes. A very considerable spread of values is seen to exist in the ratio (T) of the reliability-vector and corresponding overall error-vector magnitudes. Dividing the values of T into groups of width 0·01 units and centered on the values 0·01, 0·02 .... etc., an arithmetic probability plot (Fig. 7) may be made showing that the spread of these values corresponds very approximately to a normal distribution, and that (again very approximately) the probability of the ratio exceeding the value of 0·12 is 5%. This means that the degree of accuracy ($\pm D$) to which the shift of reproduced chromaticity of Test Colour 17 may be determined, using the chromaticity error diagrams, is approximately given by the relationship

$$D = 0{\cdot}12[(E_{uR}^2 + E_{vR}^2)^{1/2} + (E_{uG}^2 + E_{vG}^2)^{1/2} + (E_{uB}^2 + E_{vB}^2)^{1/2}]$$

This relationship is shown by the dashed line in Fig. 6.

Fig. 8 and Table 3 show the use of the chromaticity error diagrams in four practical cases, none of which gave accurate reproduction of the test colour. In Fig. 8 the individual red, green and blue error vectors are shown by full lines, and the directly-calculated error in the reproduced test colour by a single dashed-line vector. The block arrows point to the corresponding reliability vectors, each of which shows the difference between the resultant of the three error vectors on the one hand, and the directly-calculated error on the other hand. The relation between the reliability-vector magnitude and the magnitudes of the individual vectors is shown by the points A, B, C and D in Fig. 6, and it can be seen that all these points fall below the line indicating the degree of accuracy to which the use of the chromaticity error diagrams may be trusted.

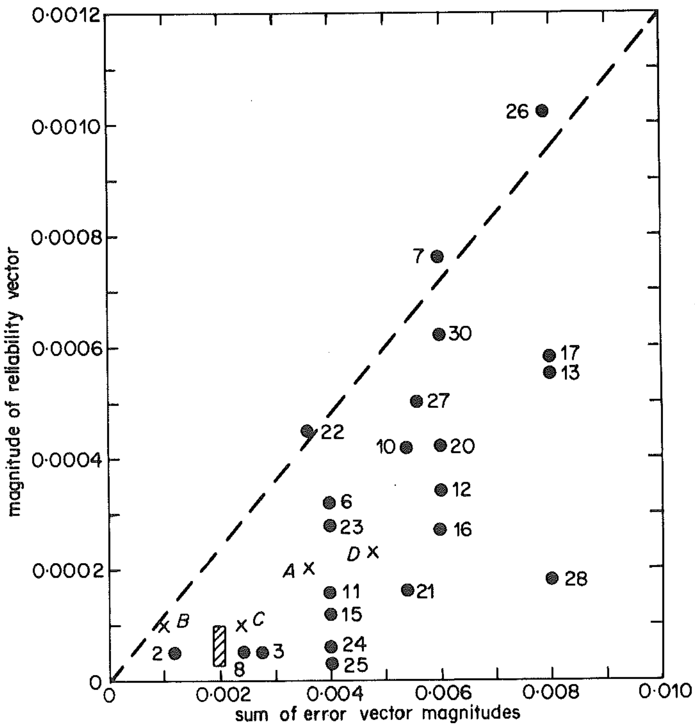

Fig. 6 - Relations between reliability-vector and error-vector magnitudes

The numbers relate to the items shown in Fig. 5

Items 1, 4, 5, 10, 14, 18 and 19 occur within the shaded area

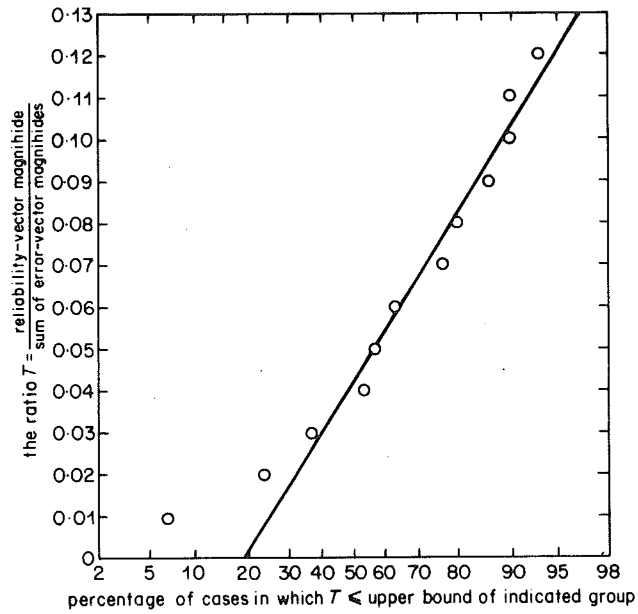

Fig. 7 - Probability plot of T-values (see text)

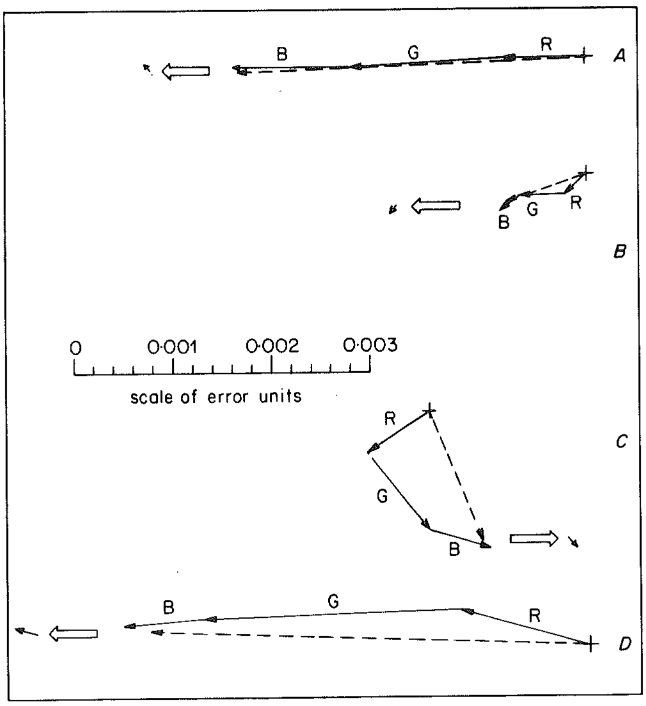

Fig. 8 - Sets of error vectors for four practical display phosphors

TABLE 3

Parameters of Four Practical Display Phosphors

Phosphor characteristics				Error in reproduced chromaticity of Test Colour 17			
Item	Primary	Co-ordinates		From chromaticity error diagrams		By direct calculation	
		u	v	E_u	E_v	E_u	E_v
A	Red	0·4231	0·3478	−0·00356	−0·00009	−0·00351	−0·00014
	Green	0·1291	0·3740				
	Blue	0·1857	0·1000				
B	Red	0·4430	0·3475	−0·00086	−0·00036	−0·00080	−0·00028
	Green	0·1233	0·3736				
	Blue	0·1761	0·1095				
C	Red	0·4298	0·3456	+0·00060	−0·00140	+0·00053	−0·00132
	Green	0·1182	0·3664				
	Blue	0·1693	0·1237				
D	Red	0·4080	0·3503	−0·00470	+0·00022	−0·00447	+0·00017
	Green	0·1339	0·3745				
	Blue	0·1818	0·1084				

3.3. Luminance error diagrams

Figs. A4, A5 and A6 (see Appendix) show respectively the red, green and blue luminance error diagrams for Test Colour No. 17. The luminance error contours are scaled in percentage luminance errors, a positive error representing an increase of luminance above the correct value. Predictions of the overall luminance error in cases where the chromaticities of two or three phosphors differ from the specified System I values are compared with directly-calculated values in Table 4. It can be seen that the greatest difference between the predicted and directly-calculated percentage luminance errors is 0·32%: this represents an imperceptible error in the relative luminance of the displayed colour, indicating that the value of relative luminance may be predicted with acceptable accuracy using the luminance error diagrams.

TABLE 4

Comparison of Predicted and Directly-Calculated Luminance Errors

Errors predicted from error diagrams (%)				Directly-Calculated Error (%)	(Predicted Error) − (Calculated Error)
Red	Green	Blue	Total		
+2·2	+0·55	+0·20	+2·95	+3·09	−0·14
+2·2	+2·00	−0·05	+4·15	+4·47	−0·32
+2·2	−1·00	+0·75	+1·95	+2·16	−0·21
−1·3	+0·55	−0·05	−0·64	−0·85	+0·21
−1·3	−1·00	+0·20	−2·10	−1·84	−0·26
−2·33	−0·75	+0·60	−2·48	−2·32	−0·16
+1·10	0	−2·45	−1·35	−1·43	+0·08
0	−0·15	−2·62	−2·77	−2·93	+0·16

4. Discussion

In some circumstances it may be sufficient to assess the colorimetric performance of a particular display solely on its ability to reproduce Test Colour No. 17 with sufficient precision. In other cases, however, it may be necessary to take into account the reproduction of other test colours: it has already been seen (Section 3.2) for instance, that some changes in primary chromaticity cause only relatively small changes in the reproduced chromaticity of Test Colour No. 17. It is therefore hoped to produce an 'atlas' of chromaticity and luminance error diagrams covering a representative selection of test colours.

5. Conclusions

A graphical method of evaluating the chromatic properties of a television display has been developed which enables the effect of changes in primary chromaticity on particular test colours to be rapidly predicted. When applied to BBC Standard Test Colour No. 17 the method has been shown to be acceptably precise and it is expected that the method can be extended to other test colours with similar success.

6. References

1. Specification of television standards for 625-line System-I transmissions, Section 5. Published jointly by the BBC and the ITA. January 1971.

2. WYSZECKI, G. *and* STYLES, W.S. 1967. Color Science, Section 3.3, pp. 235 – 6; New York, John Wiley, 1967.

3. Colour television: the adaptation of the N.T.S.C. system to U.K. standards. Part I: the colorimetry of analysis and synthesis. BBC Research Department Report No. T-060/1, Serial No. 1956/30.

4. Appendix to 'A theoretical model of a colour television display for the assessment of random noise'. BBC Research Department Report No. 1971/27.

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APPENDIX

Chromaticity and Luminance Error Diagrams for Test Colour No. 17

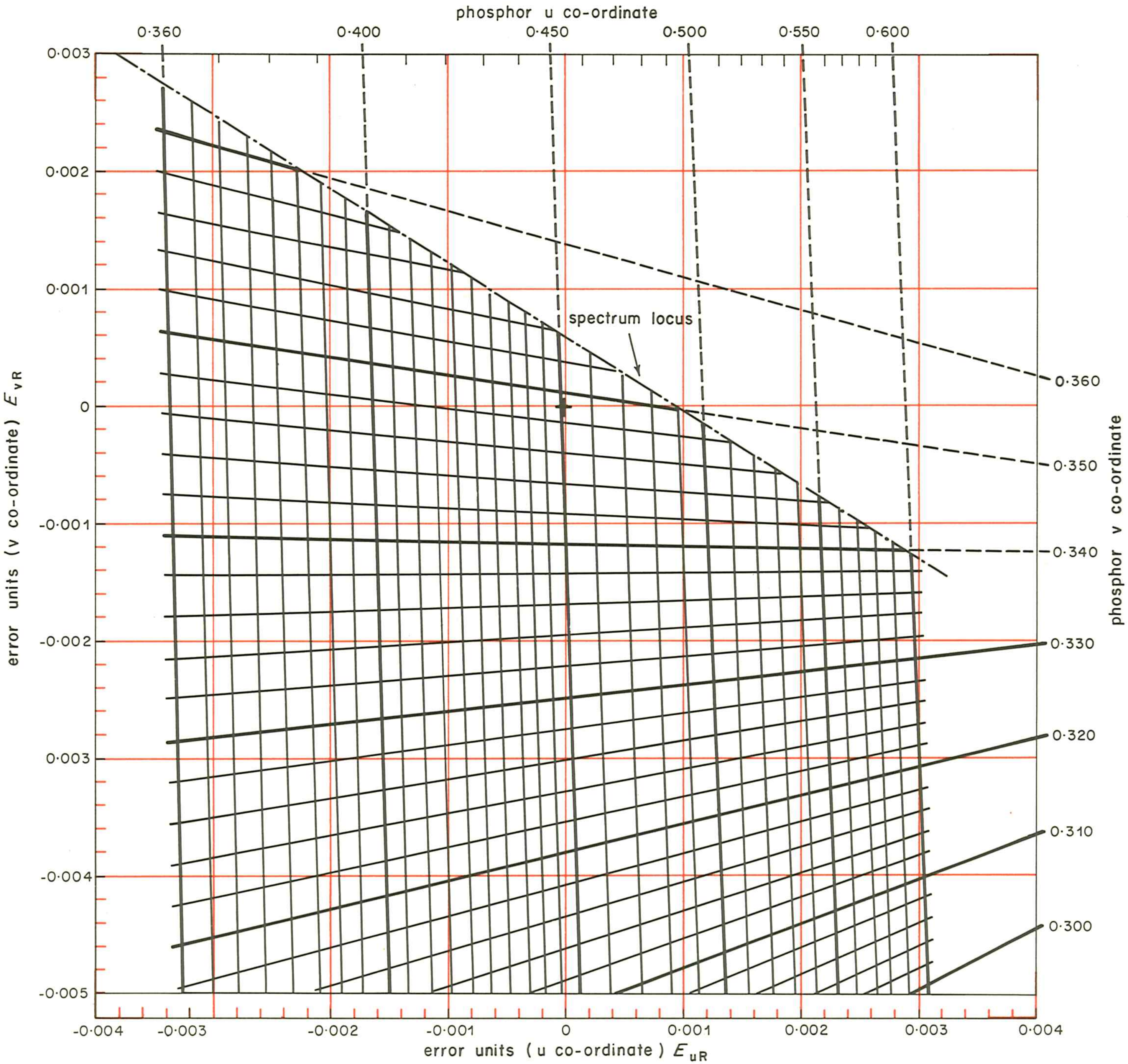

Fig. A1 - Red chromaticity error diagram – Test Colour No. 17

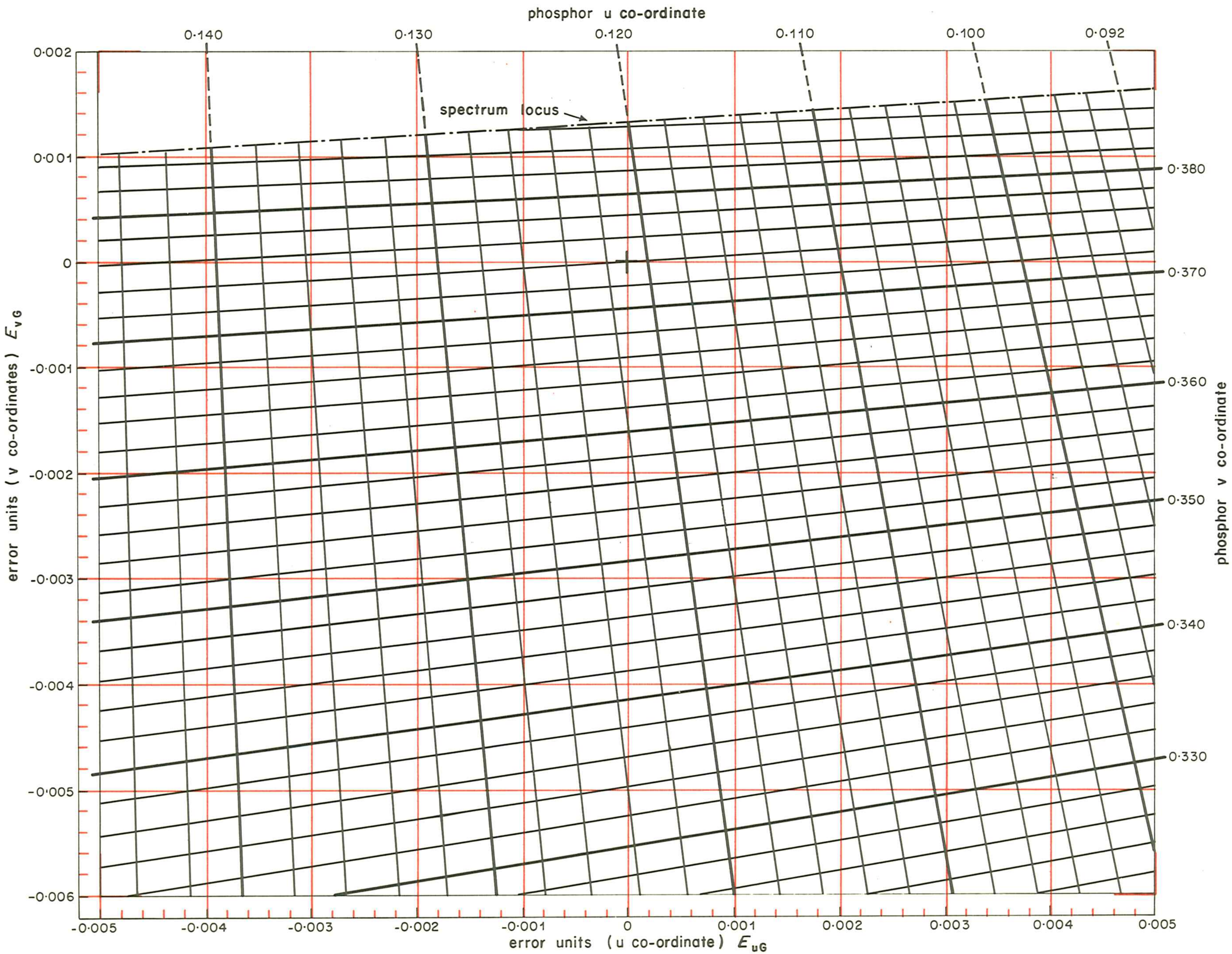

Fig. A2 - Green chromaticity error diagram – Test Colour No. 17

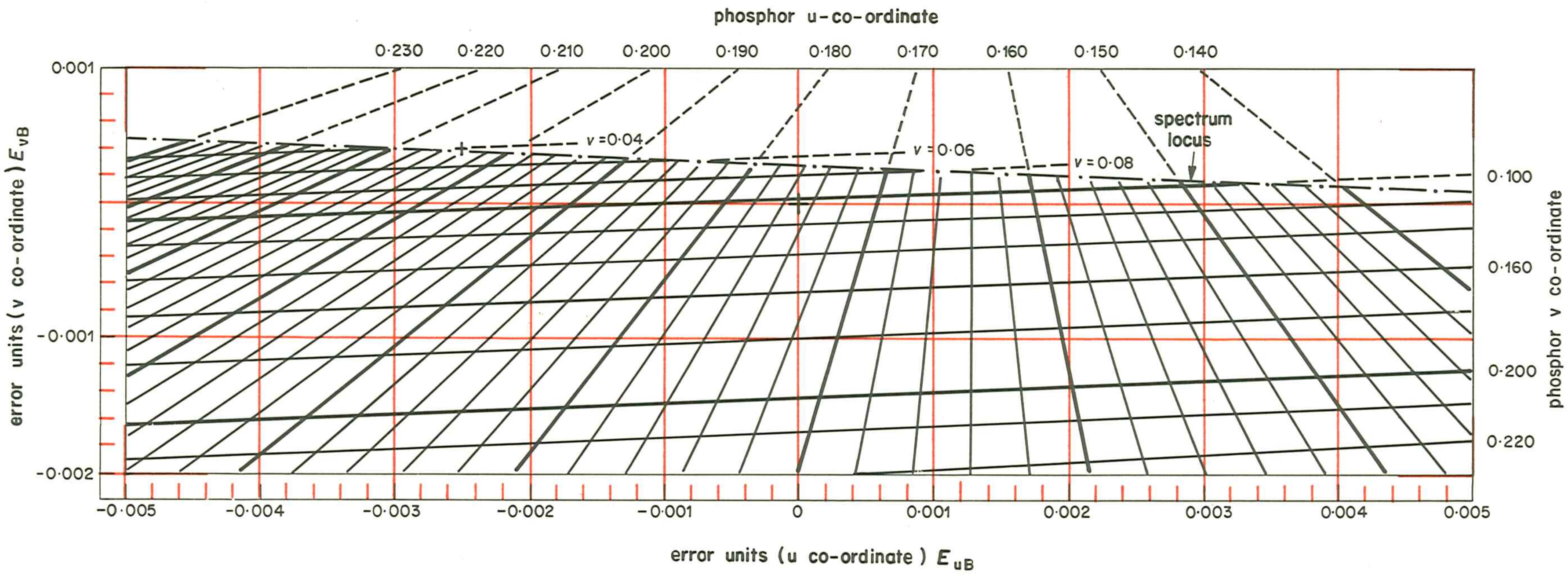

Fig. A3 - Blue chromaticity error diagram – Test Colour No. 17

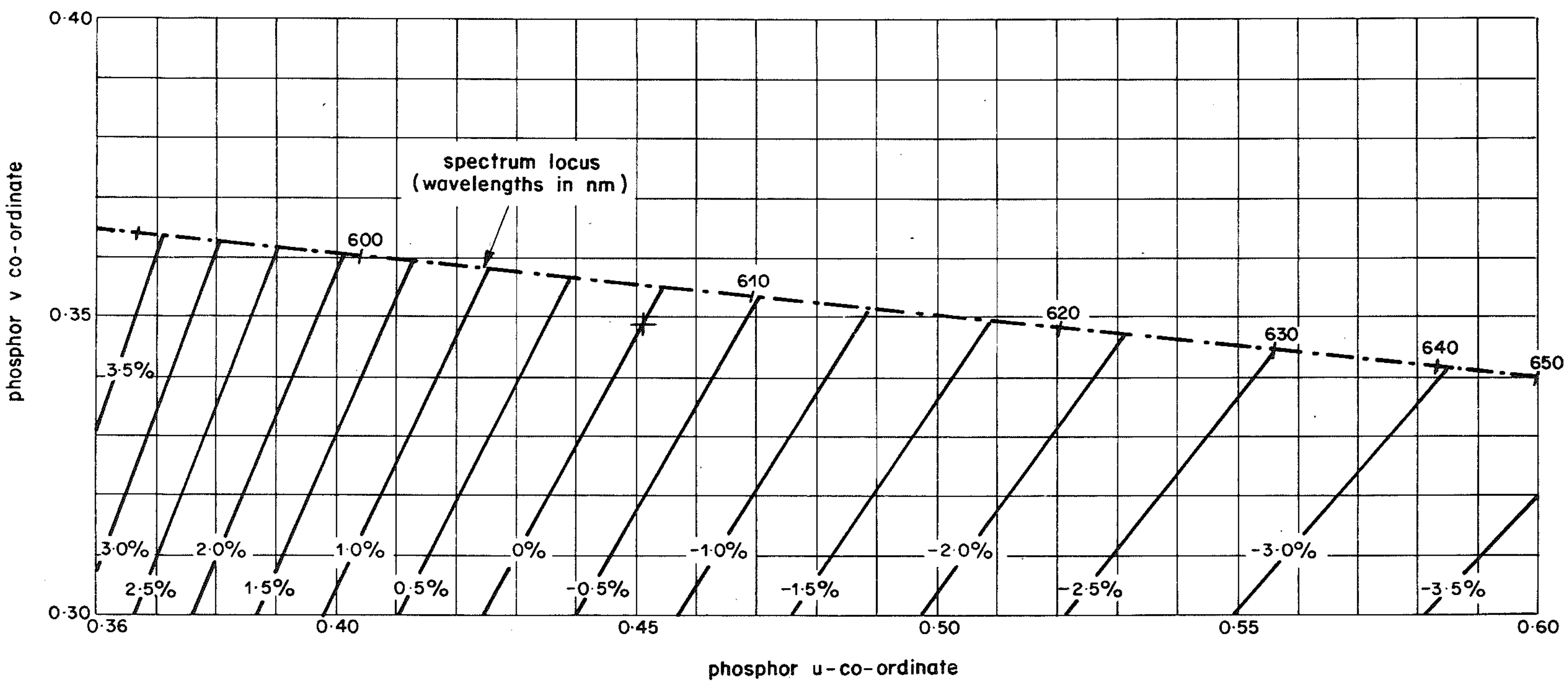

Fig. A4 - Red luminance error diagram — Test Colour No. 17

Contour values in percentage luminance error

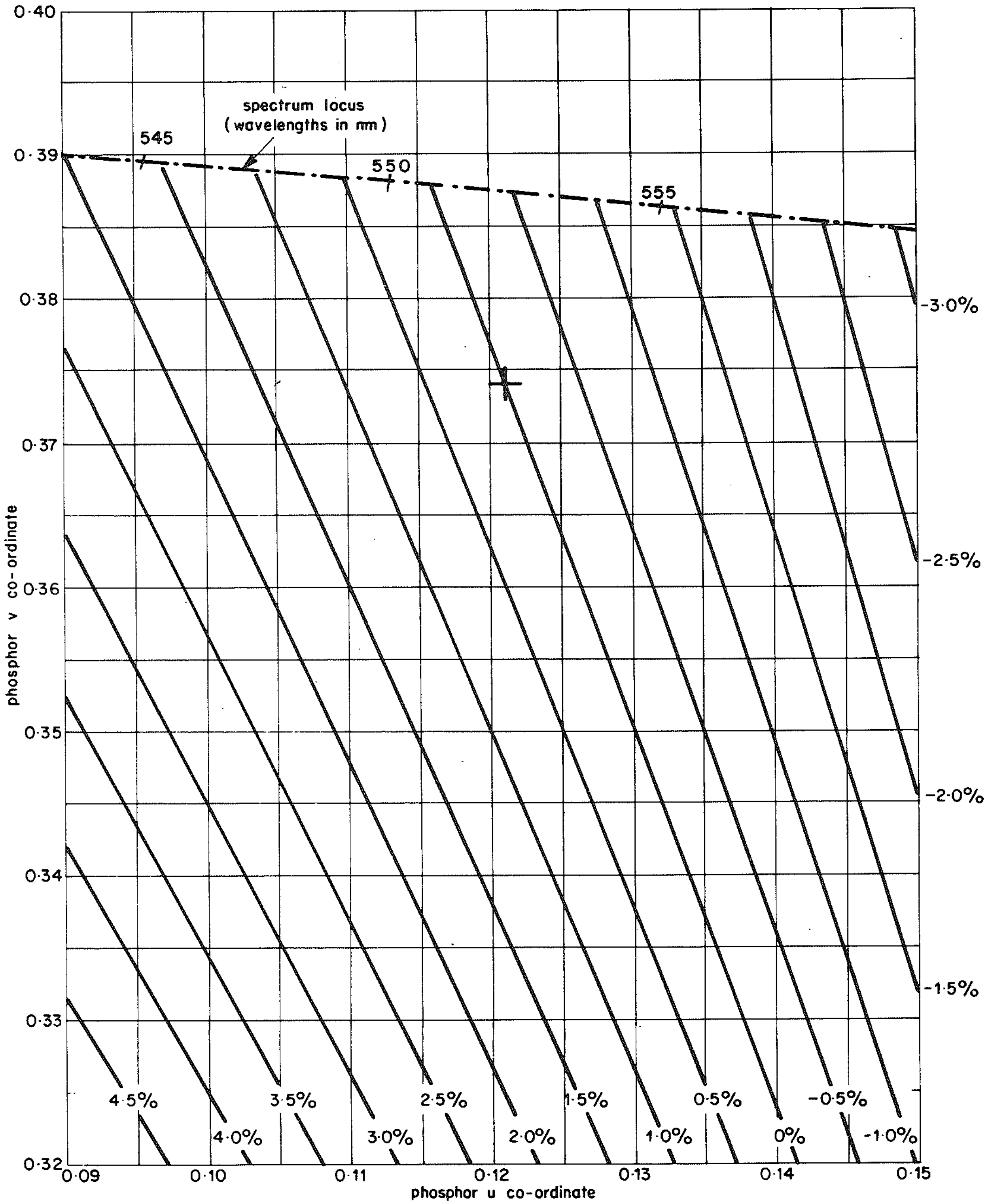

Fig. 5A - Green luminance error diagram — Test Colour No. 17

Contour values in percentage luminance error

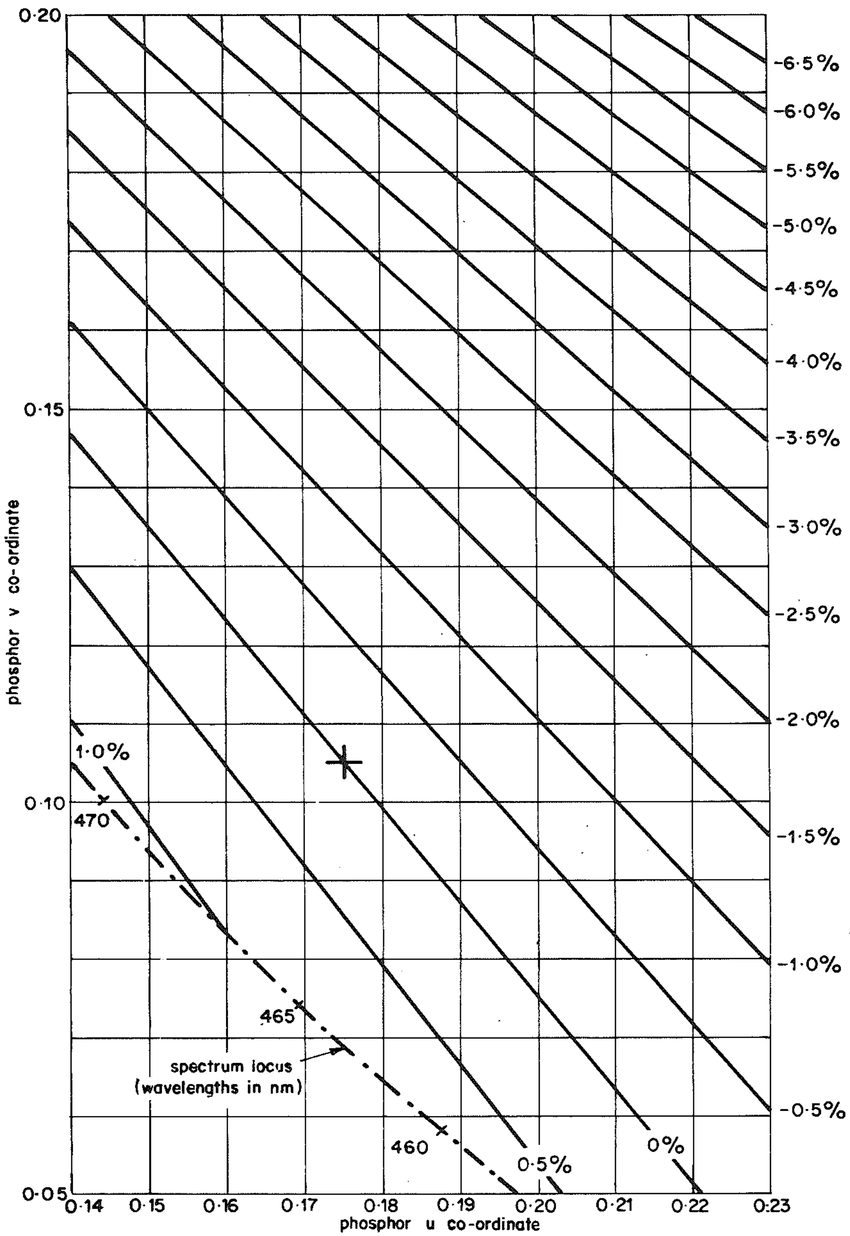

Fig. A6 - Blue luminance error diagram — Test Colour No. 17

Contour values in percentage luminance error

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